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X-Ray Observations on the Galactic Center Region

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Abstract. This paper reports on the early Chandra view of the Galactic center (GC) activities. The massive black hole Sgr A* is extremely faint, while more bright diffuse X-ray emission is prevailing in the circumnuclear disk. Another high temperature plasma is found in the Sgr A East shell. This may indicate that Sgr A East is a supernova remnant, although no clear X-ray shell is found. A hint of non-thermal X-ray filaments is found, suggesting the presence of an acceleration site of extremely high-energy cosmic rays. The giant molecular cloud Sgr B2 is established to be an X-ray reflection nebula, possibly arising from the past Sgr A activities. Chandra further discovered high temperature shells, suggesting multiple supernova explosions near the GC region.

1. Introduction

The Galactic center (GC) and its vicinity exhibit highly complex features, possibly originated from the activity of either a putative massive black hole (MBH) or violent star bursts (e.g. Genzel et al. 1994). Since X-rays usually accompany these activities, observations in this band, particularly in the hard X-rays, are vital. With the Ginga satellite, Koyama et al.(1989) discovered strong iron line emission from an extended region near the GC with a thermal energy of 10^{54} ergs and proposed that either an energetic explosion occurred at the MBH (Sgr A*), or multiple supernova explosion took place within the past 10^5 years.

The ASCA observations confirmed the Ginga results and furthermore found more detailed structures: diffuse thin-thermal X-rays of a few arcmin region in the Sgr A complex with the peak at Sgr A* and largely extended emission ($\sim 1^\circ$) with lower surface brightness. The X-ray spectrum in a $\sim 1^\circ \times 1^\circ$ region exhibits many emission lines, particularly triplet-line structure is found at 6.9, 6.7 and 6.4 keV, which are attributable to K-shell lines from H, He-like and neutral irons. The former two are due to high temperature plasmas, while the latter neutral line indicates the presence of cold gas in a strong X-ray field. However no bright X-ray source at Sgr A* and/or its vicinity has been found.

The "X-ray quiet" Sgr A* is in sharp contrast to the surrounding high temperature plasmas. The 6.4 keV line emission gives a hint to connect the quiet Sgr A* and the active environment. This emission is found to be clumpy; the brightest regions are the Sgr B2 cloud and the Galactic Center Radio Arc (Koyama et al. 1996). The Sgr C and Clump II radio sources are also found to emit 6.4 keV lines (Murakami et al. 2001a, Sakano et al. 2000). The X-ray spectra and morphologies are well explained by an "X-ray Reflection Nebula

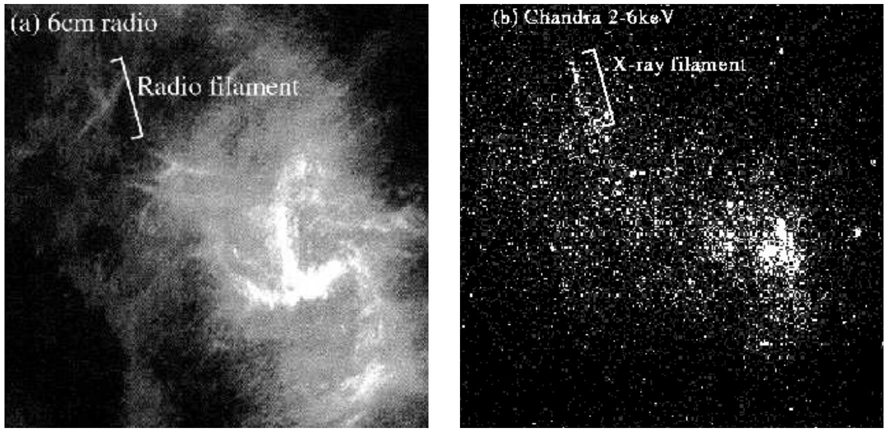

Figure 1. The radio and X-ray images near Sgr A* of a $\sim 3.5' \times 3.5'$ field. North is up and East is left. Left: The 6cm radio continuum image taken from Genzel et al. 1994 (figure 2.2), which was made from the data provided by Lo. Right: The X-ray image in the 2–6 keV band obtained with Chandra (archive: Obs ID=242). An X-ray filament is discovered near a radio filamentary structure.

(XRN)" model; the X-rays are due to reflection, photoelectric absorption and fluorescence from iron atoms. Since no adequately bright X-ray source was found in the vicinity of the XRNs to fully account for the diffuse X-ray flux, Koyama et al. (1996) and Murakami et al.(2000) proposed a scenario, despite its considerable distances from the XRNs, that Sgr A* exhibited an X-ray outburst by a possible surge of accretion on the MBH in the near past, and is currently in a quiescent accretion phase.

For further X-ray study, high resolution imaging spectroscopy on the GC region is essentially important. The Chandra ACIS-I is an ideal instrument with a spatial resolution of $0.5''$ (the size of the CCD pixel) and a reasonably large field of view of $17' \times 17'$. This paper reports the ACIS-I results of key regions near the GC based on published papers by Baganoff et al. (2001), Maeda et al. (2001) and Murakami et al. (2001), and our new analysis of the archive data.

2. Sgr A* and Its Close Vicinity

Figure 1 (left) is the radio map of the GC region of $\sim 3.5' \times 3.5'$. The large arc structure in the upper region is a part of the Sgr A East shell. The smaller shell near the right of the image is called the "Circumnuclear Disk" (CND), and inside is the "Mini-Spiral" with the center of Sgr A*. Figure 1 (right) is the Chandra ACIS image produced from the archive data (Obs ID=242). In X-rays, the brightest point source in this region is Sgr A* (near the lower right corner). Baganoff et al.(2001) reported that Sgr A* has a power-law spectrum of $\Gamma = \sim 2.7$ with an X-ray luminosity of $\sim 2 \times 10^{33}$ergs s^{-1}, two orders of magnitude lower than the upper limit measured with the previous instruments. Some point-like sources have IR counterparts, but others are unknown sources. An even

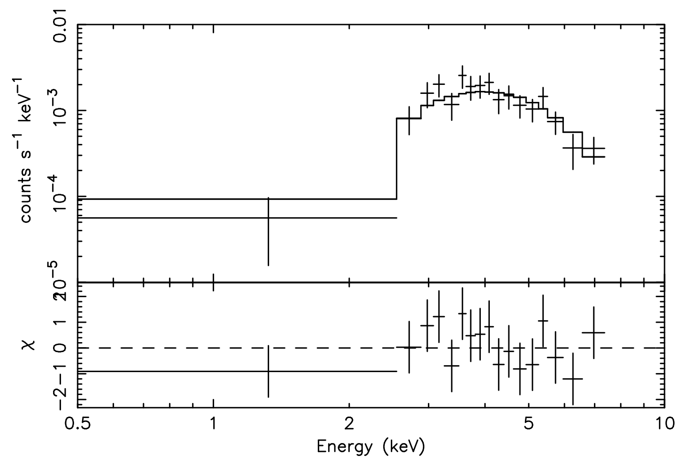

Figure 2. The ACIS spectrum of a filament in the Sgr A East SNR (see figure 1).

brighter source is diffuse emission in the CND. The X-ray spectrum is a thin thermal plasma of ~1.3 keV temperature with a luminosity of $\sim 2 \times 10^{34}$ergs s^{-1}, ten times brighter than Sgr A* (Baganoff et al.2001).

3. Sgr A East

As is shown in figure 1 (right), diffuse X-ray emission is found inside the Sgr A East radio shell. The X-ray spectrum is fitted with a 2-keV plasma model of over-abundant metals (Maeda et al. 2001). The presence of the metal-rich, high temperature plasma inside the non-thermal radio shell indicates that Sgr A East is a young SNR. No soft X-ray emission is detected from the radio shell, possibly due to the heavy absorption to this direction. For simplicity, we assume a Sedov model for Sgr A East with canonical explosion energy of 10^{51} ergs. Then the reduced age of the SNR is $\sim 10^3$ years. A notable conclusion is that the ambient density is as high as $10^{2\sim3}$ cm^{-3}. This is consistent with the fact that the radio spectrum of the Sgr A complex shows a turnover at 90 cm, which means that dense ionized gas is prevailing around the Sgr A complex. The X-ray absorptions of the GC sources are all $N_{\rm H} \sim 10^{23}$ H cm^{-2} (Baganoff et al. 2001). On the other hand, optical extinction of IR stars is $A_{\rm v} \sim 30$ mag, or $\sim 6 \times 10^{22}$ ($N_{\rm H} = 1.8 \times 10^{21} A_{\rm v}$). This apparent difference of $N_{\rm H}$ between the optical and X-ray estimations can be explained by the presence of the dense ionized gas region with a dimension of about 10 pc (Maeda et al. 2001).

We found a filamentary structure in the northern region of this young SNR. The X-ray spectrum shows no emission line, and can be fitted with a power-law model of photon index $\Gamma =\sim 2.5$ (figure 2). In the radio image of Sgr A East (figure 1 left), we find a possible radio counterpart near the X-ray filament. Another X-ray filamentary structure is found near the Galactic Center Radio Arc in the other archive data of the GC region (archive: Obs ID=945). These facts suggests that the X-ray filaments may be due to synchrotron radiation, as is

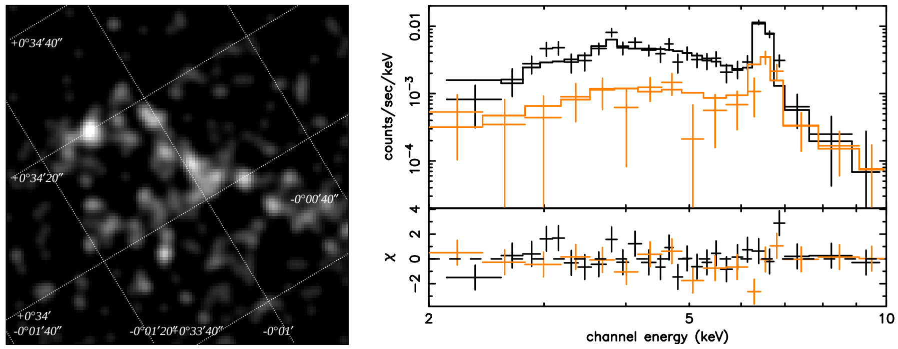

Figure 3. Left: The Chandra image of a new SNR in the 6.0-7.0 keV band. Right: The X-ray spectra of ASCA (gray line) and Chandra (black line).

seen in some shells of young SNRs, like SN1006 (Koyama et al. 1995). Since the synchrotron photon energy is given by: $E_{\rm ph} = 2[\rm keV](B/1\rm mG)(E_{\rm e}/10\rm TeV)^2$, detection of non-thermal X-rays is good evidence that extremely high-energy particles are accelerating near the GC. The energy-loss time-scale is: $T_{\rm syn} = (B/1\rm mG)^{-2}(E_{\rm e}/10\rm TeV)^{-1}$ [yr], therefore the filaments should be very young possibly $10 \sim 100$ years. Protons, of which the energy-loss is negligible, may be accelerated to even higher energy, if the magnetic field of the filaments is as high as m-Gauss. In may be noted that the Japanese Air shower group, AGASA found an enhancement of cosmic rays to the GC direction at very high energies of $\geq 10^{18}$eV (Hayashida et al. 1999).

4. New X-Ray SNRs

The superior spatial resolution of Chandra revealed that the diffuse X-rays are clumpier than it was observed with ASCA. In order to investigate the origin of the clumpy emission, we have analyzed some of the X-ray clumps. At the west of the Sgr B2 cloud, we found a small ring of $\sim 10''$-diameter (figure 3 left, Senda et al. 2001). The X-ray spectrum (figure 3 right) is well fitted with a high-temperature (6 keV) thin-thermal plasma in non-ionization equilibrium, hence the source would be a young SNR. A massive progenitor star would make a high-density gas ring in the equatorial plane and would be shock-heated by the supernova ejecta, which is essentially the same model as SN1987A (Burrows et al. 2000). In fact, if we placed this source in the Large Magellanic Cloud, we would observe an X-ray ring of $\sim 2.5''$ radius, 5 times larger than SN1987A. From the X-ray luminosity ($\sim 10^{34}$ erg s^{-1}), the ring volume (0.6 pc-radius with 0.2 pc of thickness), and the best-fit ionization parameter (log $n\tau \sim 10.3$), we can estimate the ionization age to be $\tau \sim 2{\times}10^9$ sec. Thus the X-ray ring may be the youngest SNR in our Galaxy, heated-up less than 100 years ago.

Another diffuse structure with a strong iron line is found at the south of Sgr A East associated with a non-thermal radio "wisp" (Sgr A-E) (Ho et al. 1985). The X-ray spectrum is fitted with a thin thermal plasma. We see a faint X-ray excess in a $\sim 2'$-radius circle along the X-ray shell, suggesting this to be another

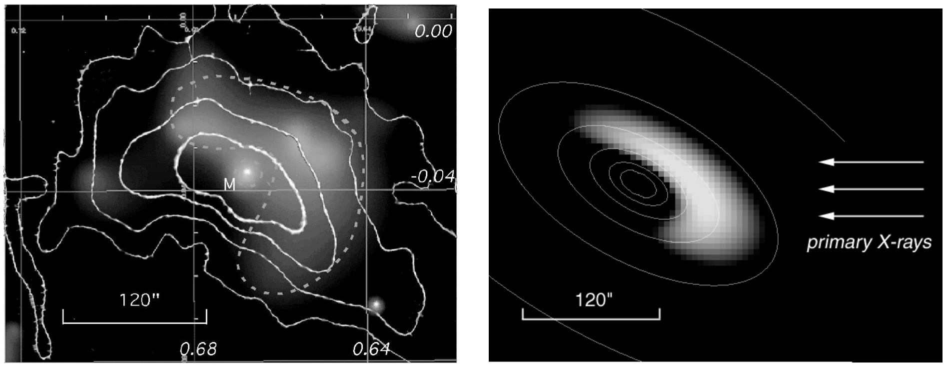

Figure 4. Left: The Chandra ACIS-I image around the Sgr B2 cloud in the 6.0–7.0 keV band. The contour shows the density distribution of the molecular cloud (Sato et al. 2000). Right: Simulated fluorescent line image based on an XRN model with the primary X-ray source at the direction to the GC (right). The contours show the density distribution.

new young SNR. We thus expect that many new SNRs will be discovered in the GC region in deep Chandra observations, which will account for a significant fraction of the diffuse X-ray emission.

5. The Role of Sgr A East to the X-ray Reflection Nebula

Among the new X-ray SNRs, Sgr A East may be particularly important. The shock wave of Sgr A East in the dense medium made a dense shell with a speed of $\sim 10^3$ km sec^{-1}. Since the projected distance between Sgr A* and the radio shell is about 1pc, the encounter would have been 10^3 years ago. What happened when the dense shell passed across the MBH (Sgr A*) ? Maeda et al. (2001) interpreted that the MBH may had been activated via Bondi-Hoyle accretion from the dense gas shell to emit strong X-rays for a few 100 years. The strong radiation field may have ionized the surrounding dense gas, which is still surviving as is noted in section 3.

At the same time, the bright X-rays from the MBH started a long distance travel. After $\sim$300 years, the strong X-rays arrived at a giant molecular cloud Sgr B2, then produced a fluorescent iron line (the 6.4 keV line) with a concave shape pointing at the GC as is given in figure 4 (left). A simulated image based on the XRN model given in figure 4 (right) is in good agreement with the observed image. The X-ray spectrum (figure 5) shows strong K_α and K_β lines with exactly the proper flux ratio of the laboratory atomic data. A deep absorption edge at 7.1 keV is also present. These results are fully consistent with the fluorescent and reflection scenario. With this scenario, we may expect many other XRNs near the GC. In fact ASCA found several other candidates, which are the Galactic Center Radio Arc (Koyama et al. 1996), Sgr C (Murakami et al. 2001a) and Clump II (Sakano et al. 2000). Chandra observations on these objects are highly required.

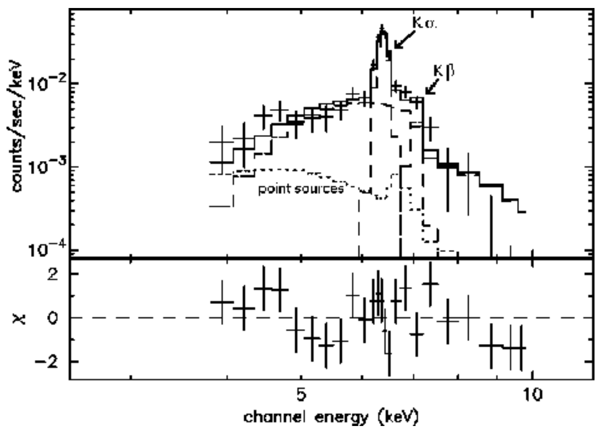

Figure 5. The ACIS spectrum of the diffuse X-rays from the Sgr B2 cloud. The dashed line indicates K_α and K_β lines, while the dotted line shows the contribution of the point sources to the diffuse spectrum.

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6. References

Baganoff, F., et al. 2001, ApJ, in press (astro-ph 0102151)
Burrows, D. N., et al. 2000, ApJ, 543L, 149
Genzel, R.,Hollenbach, D.,& Townes, C. H. 1994, Rep. Prog. Phys, 57, 417
Hayashida, N., et al. 1999, Astroparticle Physics, 303, 311
Ho, P.T.P., Jackson, J.M., Barrett, A.H. & Armstrong, J.T. 1985, ApJ, 288, 575
Koyama, K., et al. 1989, Nature, 339, 603
Koyama, K., et al. 1995, Nature, 378,255
Koyama, K., et al. 1996, PASJ, 48, 249
Maeda, Y., et al. 2001, ApJ, in press (astro-ph/0102183)
Murakami, H., et al. 2000, ApJ, 534, 283
Murakami, H., et al. 2001a, ApJ, 550, 297
Murakami, H., Maeda, Y., & Koyama, K. 2001b, ApJ, in press (astro-ph/0105273)
Sakano, M. 2000, phD thesis, Kyoto University
Sato, F., Hasegawa, T., Whiteoak, J.B., & Miyawaki, R. 2000, ApJ, 535, 857
Senda, A., Murakami, H., & Koyama, K. 2001, ApJ, submitted